Protecting Crew Members against Military Vehicle Noise

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ABSTRACT

Military vehicles can be extremely noisy working environments. Noise impairs vehicle crews in various ways, for instance through its effect on speech intelligibility and the audibility of other useful sounds. Exposure to high noise levels may, in the long run, also cause an irreversible hearing loss. An overview of interior noise levels in different types of military vehicles and aircraft shows that (extremely) high noise levels are prolific throughout the armed forces of NATO. Current developments in the field of personal hearing protection technology will contribute to limit the effects of noise on crews, the long term effects (hearing loss) as well as the immediate effects (such as the effect on speech intelligibility).

1.0 INTRODUCTION

Over the decades, the levels of noise in the military working environment seem to be increasing rather than decreasing. New vehicle types are quite often noisier than the ones they replace. At the same time, the maximum noise exposure limits required by (inter)national standards and legislation tend to become stricter. As a result, it is becoming increasingly difficult to adequately protect military personnel against noise.

The principles of noise control engineering (e.g. [4]) state that the best place to tackle a noise problem is at the source. For vehicles, this means that noise problems are best eliminated by designing engines, wheels and tracks to produce less noise. Understandably, design specifications with regard to vehicle performance, such as speed and manoeuvrability, tend to be assigned greater importance than noise production. The second-best option is to impair the *transmission* of noise, limiting the occurrence of high noise-levels to specific areas and compartments. Measures in this category that are commonly observed in vehicle design include the use of sound absorptive material (for instance in engine compartments) and adding mass and stiffness to bulkheads and panels. A more advanced technique in this category is the application of active noise and vibration control techniques, based on the principle of anti-noise, to reduce sound levels in ducts and compartments (e.g. [23]). These techniques are very appealing, but also highly complex.

After reducing noise production and limiting noise transmission, the resulting sound levels are quite often still too high. This leaves only the last line of defence against noise: personal hearing protection. Given the observed trend towards noisier vehicles and stricter standards, there is a clear challenge for research institutes and the industry to design better hearing protectors.

To deal with in-vehicle noise exposure of crew members, it is important to understand the effects of noise on man. Regulations and standards are primarily aimed at preventing hearing loss due to long-term noise exposure, but other aspects of noise exposure (such as masking of speech and other sounds) may also be

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highly important in a military environment. These issues are addressed in section 2. Section 3 aims to give and overview of noise levels for a number of categories of vehicles, to create a general impression of the degree of noise exposure (and the severity of the problems associated with noise exposure) for each vehicle category type. Section 4 discusses how existing and future hearing protective devices deal with the trade-off between protection, speech intelligibility and comfort. Finally, the role of personal hearing protection and its importance to noise exposure policy is discussed and conclusions are drawn.

2.0 EFFECTS OF NOISE ON CREWS

2.1. Different classes of noise

Noise sources are commonly categorised into two classes: impulsive noise and continuous noise. When discussing the effects of noise on man, the distinction between these classes is important: the nature and magnitude of noise effects on man is clearly different. Impulsive noises, such as explosions and gunfire, are (very) short in duration, while the peak levels can be extremely high. Continuous noises have a much longer duration. Typically, duration is measured in hours for continuous noise, and in milliseconds for impulsive noises. Peak levels for continuous noises are normally not as high as for impulsive noises. While peak level can be a suitable measure to predict the severity of the effects of an impulsive noise on man, other measures are preferred to predict the effects of continuous noises.

Noises produced by vehicles are predominantly continuous noises. However, impulsive noises may sometimes be expected to occur in vehicles, for instance resulting from gunfire. Since these noises are not typically related to the use of the vehicle itself, they are not discussed in this paper. When impulsive noises regularly occur in addition to the “normal” vehicle noises discussed here, the guidelines and overviews presented in this paper may be too optimistic.

2.2. Effects of vehicle noise on hearing acuity

Prolonged exposure to loud noises may reduce the sensitivity of the human ear. This becomes apparent as an upward shift of the hearing threshold: after exposure to noise, sounds need to be louder in order to be observed. A distinction is made between temporary effects (temporary threshold shift or TTS) and permanent effects (permanent threshold shift, PTS). TTS is experienced immediately after exposure to noise, and “wears off” after a number of hours. There are strong indications that people who find themselves particularly susceptible to TTS are also at increased risk of acquiring PTS (e.g. [22]).

PTS, also indicated as noise-induced hearing loss, is irreversible. It is often be acquired insidiously, without experiencing any severe acute effects immediately after exposure. This type of hearing loss is a result of damage done to the hair cells in the inner ear, which are responsible for converting sound into neural signals. There is no therapy to repair damaged hair cells.

There is a normal trend for the hearing threshold to shift upward with age: the average 18-year old is able to perceive much softer sounds than the average 65-year old [7]. Any noise-induced hearing loss acquired during one’s life is added to this normal threshold shift with aging. In other words, a hearing loss that is acquired at a relatively young age inevitably grows as one ages [16]. This means that a degree of noise-induced hearing loss that is not experienced to be very troublesome at first, may develop into a serious problem simply with time.

Noise exposure measures for continuous noise apply a frequency-weighting filter to account for differences in sensitivity of the human ear for different frequencies. Also, an energetic summation procedure is used to take the accumulation of the noise dose during prolonged exposure into account. The most widely accepted measure to express exposure to continuous noise is the A-weighted equivalent-

continuous sound pressure level (L_{Aeq}). Common exposure limits for an eight-hour working day [6], in terms of L_{Aeq}, are 80 or 85 dB(A). For every 3 dB that a measured L_{Aeq} exceeds the limit, the maximum exposure time must be halved[1]. This means, for example, that a measured L_{Aeq} of 86 dB(A) in a situation where the limit is 80 dB(A), requires limiting the maximum daily exposure time to 2 hours instead of the normal 8 hours.

There are individual differences in the susceptibility to noise-induced hearing loss. At the moment, these individual differences are incorporated into noise exposure standards by relating maximum noise levels to a certain percentage of the population that is allowed to be at risk. At a limit of 80 dB(A), for instance, 5% of the population is still presumed to be at risk of hearing damage [6]. Since protecting 100% of the population is not feasible (some very sensitive people may be affected even by the noises of everyday life), the decision on what percentage of the population may be allowed to be at risk for hearing loss may continue to be a debate.

The problem described above, hearing loss as a result of occupational exposure to noise, is essentially a health issue. However, the prevalence of PTS and TTS in a population of soldiers also has operational applications. A group of infantry soldiers suffering from TTS, as a result of transportation in a personnel carrier, will also be less able to detect and identify certain sounds, such as walking noises and distant gunfire.

2.3. Masking effects of noise on warning signals

The audibility and recognisability of sounds is often reduced by the presence of noise. A straightforward parameter used to predict detectability of sounds in noise is the signal-to-noise ratio (SNR), usually expressed in decibels. Humans are quite proficient at separating useful signals from noise; we are often able to hear these useful sounds, even if these are presented at a level that is lower than the sound level of the noise (that is, even at negative SNRs; e.g. [10]). However, there are indications that signals that are just above the detection threshold (and *can* in principle be heard) require a greater degree of attention, and are more likely to be missed under stressful conditions, than sounds that are well above the detection threshold [3].

For this reason, it has been recommended ([8],[14]) that the SNR for danger and warning signals should be at least 15 dB (that is, the A-weighted sound level of the warning signal should exceed the A-weighted level of the noise by at least 25 dB). To prevent startle reactions and to limit the invasiveness of the signals, it is also recommended that the SNR should be no higher than 25 dB.

The implication of all this is that well-designed warning signals, in order to be audible, are presented at sound levels well above the level of the noise itself, potentially contributing considerably to the overall sound exposure. If these warning signals rarely occur, or the duration of the warnings is very short, the effect on the overall noise dose may remain small. In all other cases, the influence of warning signals (and other sounds presented to crew members) should be explicitly addressed.

2.4. Effects of noise on speech intelligibility

For crew members of military vehicles, speech communication is often literally of vital importance. Radio channels and intercommunication systems are relied upon to quickly and efficiently exchange information, between crew members and with the outside world. If the experienced speech intelligibility becomes too low, dangerous situations may arise.

[1] Other exposure limits than 80 or 85 dBA are also found in standards, while other exchange rates (5 dB instead of 3 dB per doubling of the exposure time) also occurs in some (mainly US) standards.

Unless the SNR is very high (> 15 dB), the intelligibility of speech is always reduced by the presence of noise. The precise impact that vehicle noise has on speech intelligibility can not be predicted accurately by the SNR alone. In reducing the overall intelligibility, noise interacts with other speech-degrading factors such as audio bandwidth limiting, channel distortion and vocoder artefacts. The resulting overall intelligibility can be evaluated using an array of different subjective measurement techniques (e.g. [20]). In many cases, it is possible to efficiently measure or predict speech intelligibility using objective speech intelligibility evaluation methods, such as the Speech Transmission Index [5].

The effects of noise on speech intelligibility also depends on the population of talkers and listeners. If speech communication is taking place in a language that is not everybody's native language, as commonly happens in international military operations, the effects of noise on speech intelligibility are aggravated [19].

By far the easiest way to improve speech intelligibility in noisy conditions is to increase the speech level. The fact that speech intelligibility is considered to be highly important often leads crew members to adjust the volume controls of intercom and radio systems to very high settings, sometimes corresponding to speech-to-noise ratios in excess of 10 dB [9,18].

In order to assess any trend in comms load with aircraft type the average comms contribution and the associated standard deviations were calculated for some aircraft that have been surveyed by QinetiQ. The results are shown in Table 1. Although the comms contribution to overall noise dose appears to be relatively small compared to that contributed by the ambient noise reaching the ear, it is important to remember that it is additional to the background noise, effectively riding on top of the background signal. If no comms were present throughout, for example, a Harrier flight, the aircrew could fly 10 times as long for the same risk of hearing damage, i.e. the comms is making a significant contribution.

Aircraft Category	Aircraft Type	mean comms dB(A)	Sdev comms dB(A)
Helicopters	Sea King Mk5	6.3	2.2
	Sea King Mk4	7.9	1.4
	Sea king Mk6	7.1	2.0
	Lynx Mk7 & Mk9	9.8	2.5
	Chinook HC1	8.6	2.6
Fast jets	Harrier GR5	10.0	4.3
	Jaguar GR1	9.9	4.2
	Tornado	10.4	2.9
	Hawk	9.1	3.2
	Sea Harrier	9.1	2.7
Training	Tucano	8.5	1.8
Transport	Hercules C1/C3	8.4	3.0
	HS125	10.6	4.8

Table 1. The overall mean communications contribution figure calculated for each aircraft type

Especially in situations where voice communications are frequent, a significant contribution is made to the overall noise dose. This implies that it is worthwhile to invest in high-quality communication systems; better communication systems (wider bandwidth, less distortion) are able to offer the same intelligibility at lower speech levels.

3.0 NOISE LEVELS TO BE EXPECTED IN MILITARY VEHICLES

3.1. Noise level measures

We have been using the term "noise level" loosely, implying that the effects of noise can be predicted by some simple estimate representing the overall sound level. This is often true (for instance, when using the L_{Aeq} to calculate maximum daily exposure times). In other cases a more elaborate parameterisation of the noise is needed, for example when predicting speech intelligibility in noise using the Speech Transmission Index.

To quantify the overall impact of noise, in principle the characteristics of this noise in the time domain as well as in the frequency domain are relevant. Time domain characteristics are quite often ignored when considering continuous noise issues. However, particularly for speech intelligibility these differences may be relevant. For instance, steady-state noise of a given A-weighted level has a greater impact on speech intelligibility than fluctuating noise of the same A-weighted level [2].

Fortunately, for most applications, considering the characteristics of the signal in the frequency domain is considered sufficient. The linear sound pressure level obtained through (unweighted) energetic sum across the entire frequency range, the acoustic equivalent to the root-mean-square (RMS) voltage used in electronics, is not a good predictor of noise effects on man. This level (linear SPL), although routinely reported, may be determined by frequencies that have little importance to the perceiver, because of the frequency-dependent sensitivity of the human ear.

To fully represent an acoustic signal in the frequency domain, the energy at any frequency must be measured: the acoustic spectrum. Although it is technically feasible to obtain spectra with a very high frequency resolution, a 1/3-octave band spectrum (such as shown for the Chinook helicopter in Fig. 1) is sufficiently detailed for assessing the various effects of noise (risk of hearing loss, masking, intelligibility).

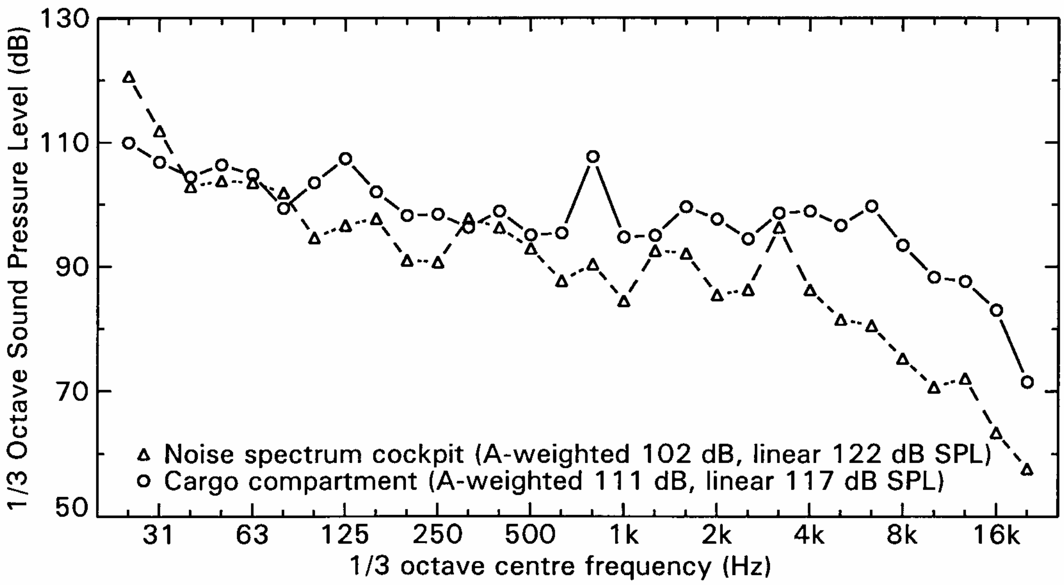

Figure 1. 1/3-octave noise spectrum inside RNLAF CH47-D Chinook helicopters, in two different positions (cockpit and cargo compartment). The A-weighted and linear sound pressure levels are also indicated.

Unfortunately, the most widely used acoustic measuring devices (sound level meters) do not offer the possibility to measure the acoustic spectrum. Moreover, the interpretation of spectra such as the one shown in Fig.1, which can be presented as complex graphs or tables, is not always easy. With respect to this, using a single level parameter has great advantages. By applying frequency-weightings, such as the A and C-weightings, which take sensitivity differences of the ear into account, meaningful single-number representations of the noise level can be obtained. Particularly A-weighted sound pressure levels have been shown to predict loudness and exposure risks with good accuracy.

3.2. Overview of noise levels for vehicle categories

In most NATO member nations, an overview of vehicle noises in the various military vehicles will be available in some form or another. These overviews are not routinely exchanged or published, which means that insight into noise exposure in the armed forces exists, at best, on a national level. Moreover, procedures to calculate noise data, as well as the level of detail that is reported, varies from nation to nation.

The most useful common denominator across various noise surveys is the A-weighted noise level at the positions of exposed crew members. Nearly all surveys report this measure, as it can be used as a fairly good first-order indicator of noise exposure.

Unpublished and published noise survey data for land- and air vehicles was collected from various sources. National surveys from BE, CA, FR, NL, UK and US [17] where included, as well as a limited-size NATO-wide survey [12] and a non-NATO study featuring data on vehicles also used within NATO [13]. The collected data should serve to create a general impression of the average noise level for each vehicle category, as well as the statistical spread within categories. The combined data are presented in Figs. 2 (land vehicles) and 3 (aircraft).

For each vehicle type, multiple measurements will normally be available, representing different positions (driver, copilot, passenger, navigator,…) and different conditions (70 km/h, 400 knts, hovering, …). Since the measurements conditions were quite different for different vehicle types, the worst-case conditions were chosen for each vehicle rather than presenting multiple conditions (which would be hard to compare). These worst-case conditions correspond to the maximum performance (e.g. in terms of speed), or the most disadvantageous mode of operation (such as helicopter hovering, or moving with doors or hatches opened). Whenever multiple positions where available, the position closest to crew member who is expected to spend the most time in the vehicle was taken. This would normally be a driver or pilot position.

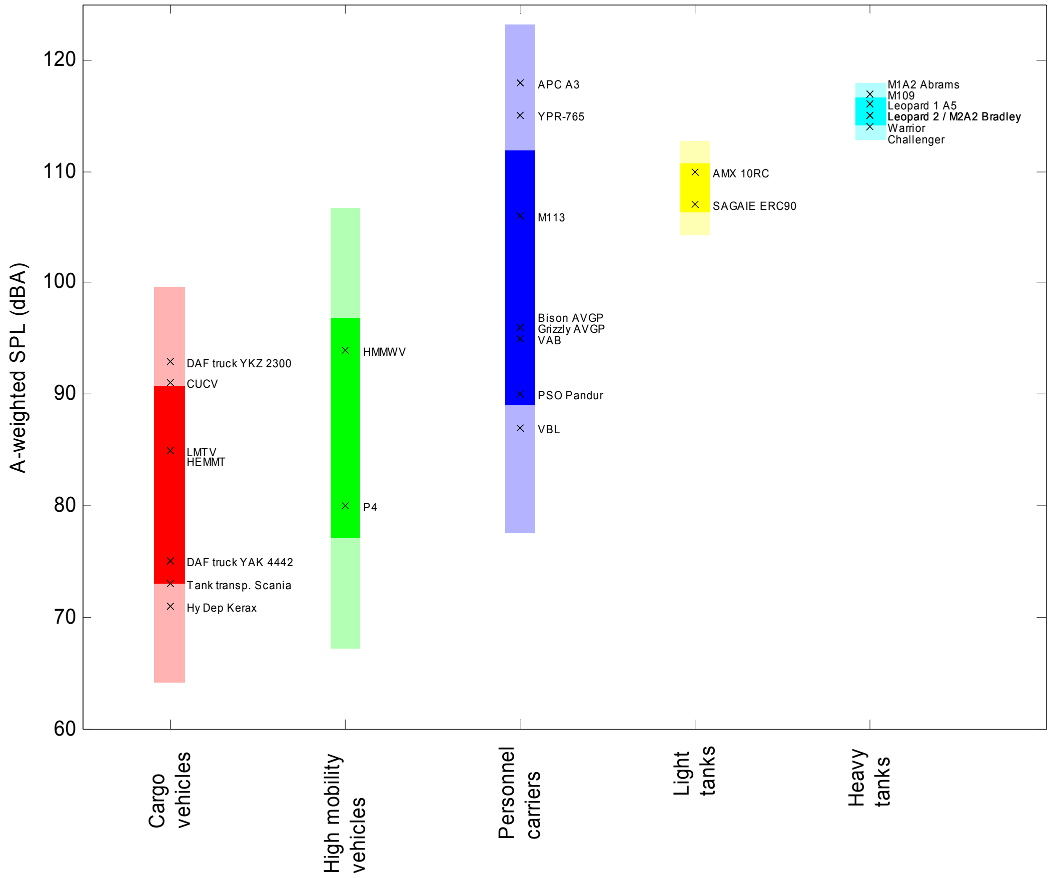

Figure 2. A-weighted interior noise levels for 26 land vehicles (used by various NATO nations), grouped by category. The dark coloured bars span two standard deviations within each category, the combined dark and light bars span four standard deviations. Interior noise levels for specific vehicle types are indicated by 'x' symbols with corresponding text labels.

The dark coloured bars in Figs. 2 and 3 (the middle section of each bar) span two standard deviations around the mean A-weighted sound level (the mean $\pm$ one standard deviation). Statistically, 68% of all vehicles in each category is expected to have an A-weighted sound level that falls within this region. For the combined length of the dark and lighter parts of the bars (the full length, corresponding to four standard deviations), this expected percentage is increased to 95%.

For the land vehicles, a clear trend is that the heavy armoured vehicles ("heavy tanks") show the highest interior noise levels. Perhaps more surprising, the spread between various types within this category is quite small. It seems fair to say that heavy tanks are noisy, but all to approximately the same degree. For the armoured personnel carriers (referred to from hereon as APCs), the average is lower, but the statistical spread is much greater. This means that it will be hard to provide an educated guess for the interior noise levels in any of these vehicles, unless specific measurements are available. What should be noted, although this is not presented in Fig. 2, is that noise levels in APC passenger compartments were found that were up to 8 dB lower than the levels the driver is exposed to (which were used for Fig. 2).

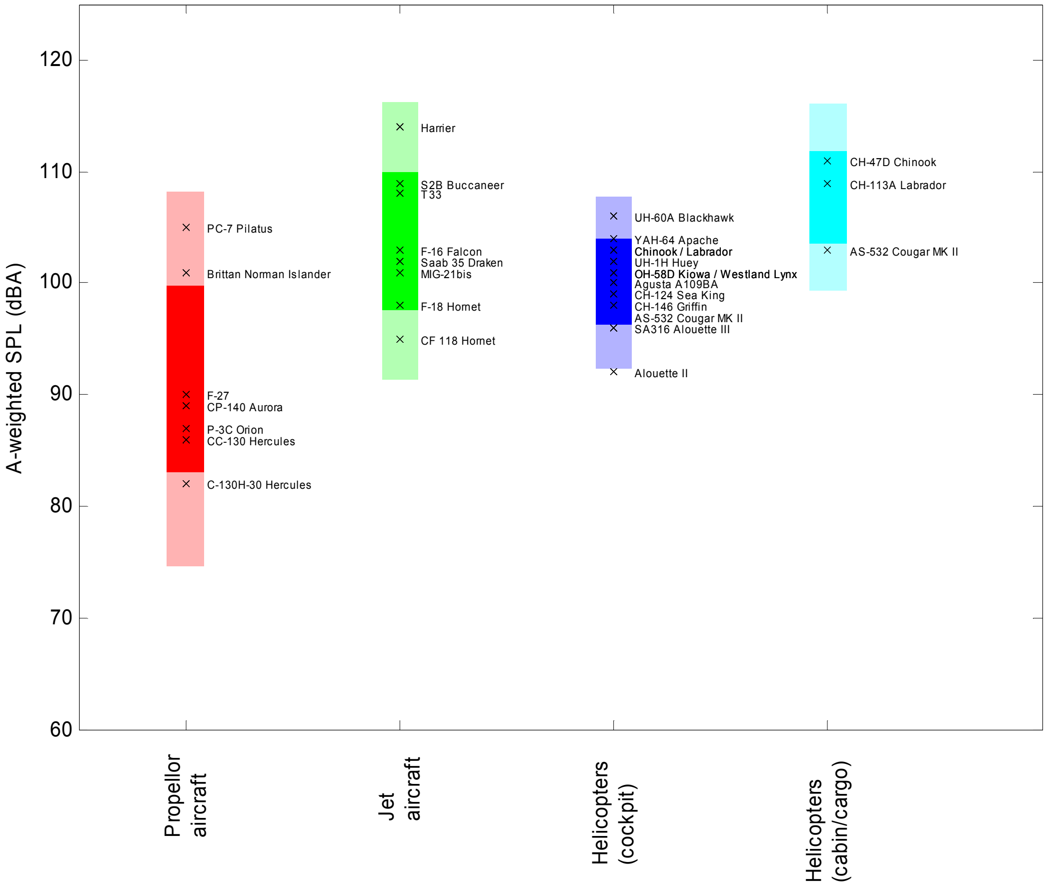

Figure 3. A-weighted interior noise levels for 26 aircraft types (used by various NATO nations), grouped by category. For three helicopter types where the noise levels inside cargo compartments or cabins clearly differed from the cockpit noise levels, these levels were reported as a separate category. The dark coloured bars span two standard deviations within each category, the combined dark and light bars span four standard deviations. Interior noise levels for specific vehicle types are indicated by 'x' symbols with corresponding text labels.

The category in Fig. 3 with the highest mean *cockpit* sound level is the "jet aircraft" category (although the helicopter cabin/cargo levels are even higher). For the propellor aircraft, the spread is considerable. The top two aircraft in this category are considerably smaller than the others, suggesting a trend for smaller propellor aircraft to be relatively noisier. It is also interesting to note that, in larger helicopters, cockpit crews are likely to be exposed to much lower noise levels than crew members operating in the rear of the helicopter (such as loadmasters and gunners). For the helicopter (cockpit) category, there is a general trend for larger, heavier helicopters to be noisier.

Of course, collected data as presented in Figs. 2 and 3 offer no replacement for measurements in the specific vehicle for which one is interested in finding out about noise exposure, in the specific conditions it will be used in. However, these data may be helpful in arriving at an educated guess for the noise levels of vehicles for which noise data are otherwise unavailable.

3.2. In-situ noise dose measurements

In the previous sections we argued that the A-weighted noise levels inside vehicles are useful as predictors of noise exposure. This is literally true if no hearing protection is used at all: the data of figs. 2 and 3 can then be interpreted directly as noise exposure levels in the sense of ISO 1999. If hearing protectors *are*

used, the interaction between the spectrum of the noise and the frequency-dependent characteristics of the hearing protector also play an important role.

At least two avenues lead to an estimate of the continuous equivalent A-weighted sound pressure level as used in ISO 1999 for protected ears, allowing direct comparison to an exposure limit. The first - and probably the easiest - way requires that the ambient noise spectrum (as in Fig. 1) has been measured. By subtracting the measured or specified frequency-dependent sound attenuation of hearing protectors, and calculating the overall A-weighted level from these frequency-dependent data, a result is obtained that can be compared to A-weighted noise exposure limits. It is important to note that the hearing protector attenuation to be used in this calculation is not the *average* attenuation for a specific type of hearing protector, but rather the average minus one standard deviation. This is done to decrease the percentage of the exposed population that is at risk, since the attenuation of a hearing protector tends to vary from person to person. By working with the average attenuation, the actual attenuation would effectively be underestimated for 50% of the population. By reducing the measured attenuation by one standard deviation, this percentage is reduced.

The second way to obtain a noise exposure estimate is by carrying out in-situ noise dose measurements. This is more complicated, but also more reliable; the resulting noise dose is then obtained under the most representative conditions, and no assumptions about equivalence of lab conditions to operations in the field are made. Several published case studies (e.g. [13],[18]) have shown that real-life noise doses, measured in situ with specific devices (dosimeters), turn out higher than predicted from sound attenuation values measured in the lab. At least a number of reasons for this difference can be identified. First of all, a large contribution to the overall noise dose is made by intercom and radio communications. As noted above, crew members adjust volume controls to very high levels, which can even objectively be shown to be higher than needed for a sufficiently good speech intelligibility [18]. A second reason is that sound attenuation specifications are based on correct use of the hearing protection equipment, exactly according to procedures. Under operational conditions, these procedures are not always strictly adhered to. Finally, hearing protection devices are subject to wear and tear, which may lead their performance in practice to decrease over time.

4.0 HEARING PROTECTION: THE AVAILABLE OPTIONS

4.1. Model of hearing protection

Today, a diversity of hearing protective devices is commercially available, ranging from the simplest earplug to sophisticated digital noise-cancelling headsets. The primary function of these devices is always to reduce the exposure of the user to ambient noise. Which option is the most effective depends strongly on the application.

To illustrate how the various hearing protection alternatives work, and in particular how they affect speech intelligibility, a simple model is presented in Fig. 4. This figure represents the head of a crew member wearing a helmet with integrated hearing protection (earcups).

Sounds, unwanted as well as useful, are only perceived once they reach the inner ear. This organ performs a spectral analysis of sound and translates it to a neural code, for further processing by the central nervous system. The sensitive cochlear hair cells used in this process may become damaged through exposure to high sound levels. This generally gradual process is what causes noise induced hearing loss.

To prevent noise from reaching the inner ear, its path must be blocked acoustically. Sound attenuation earmuffs or earcups, used as a headset or integrated into a helmet as in Fig. 4, are the most commonly applied hearing protectors used in vehicles. In earmuffs, rigid plastic shells cover the entire outer ear, sealed off around the edges by means of circumaural pads (rings filled with elastic material, pressed

against the head by the earcup). If properly fitted, earcups can be comfortable and effective. However, there is a limit to the degree of protection that can be offered: the maximum attenuation, especially at low frequencies, is often insufficient to meet noise exposure limits. The outer shells of helmets, provided for impact protection, offer no protection against noise (and may even introduce a small amount of amplification at certain frequencies).

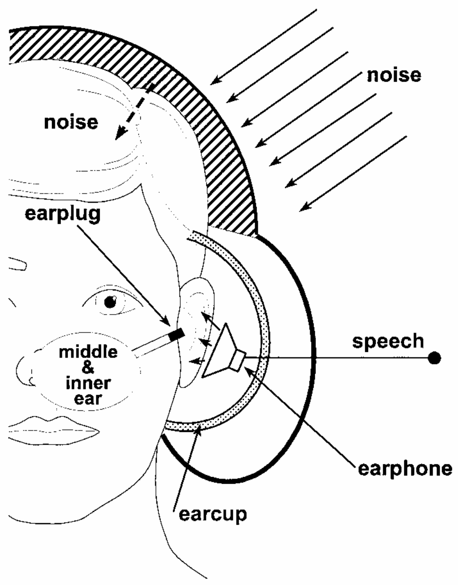

Figure 4. Model of personal hearing protection

Since all sounds normally reach the inner ear through the middle ear and the ear canal (shown very schematically in Fig. 4), blocking the ear canal with an earplug is a straightforward option. However, earplugs have a number of disadvantages. Most importantly, earplugs attenuate *all* sounds without discrimination. If speech signals (from radio or intercom) are presented, for instance through earphones as shown in Fig. 4, these are attenuated to the same degree as the ambient noise. The earphone sound level needs to be adjusted to compensate for the attenuation of the earplug. In practice, this often means that the earphones will be operating at sound levels at which the speech becomes considerably distorted. This reduces the overall speech intelligibility experienced by the user.

In the harshest of noise environments, it is not possible to reach exposure limits with earplugs or earcups alone. An option is to combine both types of hearing protection, as shown in Fig. 4. ("double hearing protection"). Even this may be insufficient; if the combined attenuation of the hearing protectors is very high, alternative conduction paths (through bone and tissue [24]) may contribute significantly to the overall noise exposure (as symbolised by the dashed arrow in Fig. 4). This imposes an upper limit to the maximum degree of sound attenuation that can effectively be provided.

4.2. Choosing a compromise

Selecting a hearing protector for a certain application comes down to choosing a compromise. It is not a good idea to simply pick the alternative that offers the highest possible sound attenuation. This will indeed provide the best possible protection against noise, but potentially at the expense of speech intelligibility and user comfort.

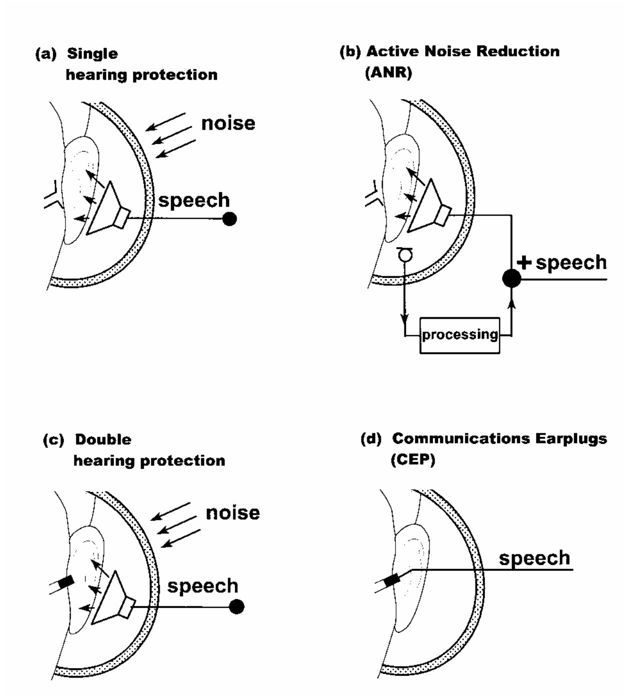

Figure 5. Four different categories of hearing protectors

Four different hearing protection principles, shown in Fig. 5, will be discussed below.

4.2.1. Single hearing protection

Single hearing protection can be either a simple earplug, or (more likely for vehicle crew members) a headset or helmet with sound attenuating earmuffs. The degree of sound attenuation varies, depending on the quality of the earmuffs. Attenuation curves of a helmet and a headset (typical examples) are shown in Fig. 6. This figure clearly shows that the amount of sound attenuation in the low-frequency region is limited. This especially leads to exposure problems in vehicles with prominent low-frequency noise components, due to heavy combustion engines (e.g. tanks) and helicopter rotors.

4.2.2. Active noise reduction (ANR)

When applying Active Noise Reduction (ANR) in headsets, an electronic circuit is used that exploits the principle of anti-noise to reduce noise levels inside earcups (e.g. [15]). A sense microphone inside the earcup (Fig. 5b) picks up the sound, and plays it back in anti-phase through an earphone. Intercom speech can be added, to be played back through the same earphone.

ANR offers an additional reduction of the noise level in the earcup, on top of the passive attenuation offered by the earcup itself. However, this only works at lower frequencies (up to 1000, or at best 2000 Hz).This is illustrated by Fig.7, which shows the attenuation of an ANR headset with the ANR circuitry switched on and off. ANR can nicely fill the low-frequency “gap” in attenuation of earcups.

As can be concluded from Fig. 7, ANR should only be used in the noise spectrum is predominantly low-frequent. If the noise spectrum shows significant contributions around 1000-2000 Hz (where ANR actually amplifies the sound somewhat), ANR could even increase instead of reduce the overall noise level.

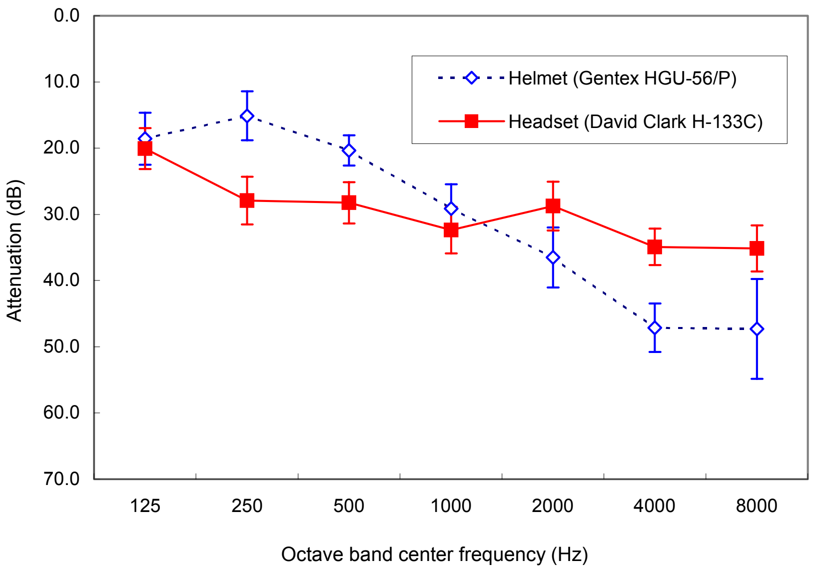

Figure 6. Sound attenuation curves for typical examples of a helmet and a headset, measured according to ISO 4869-1 (1990) with a frequency resolution of 1 octave. The error bars indicate the standard deviation.

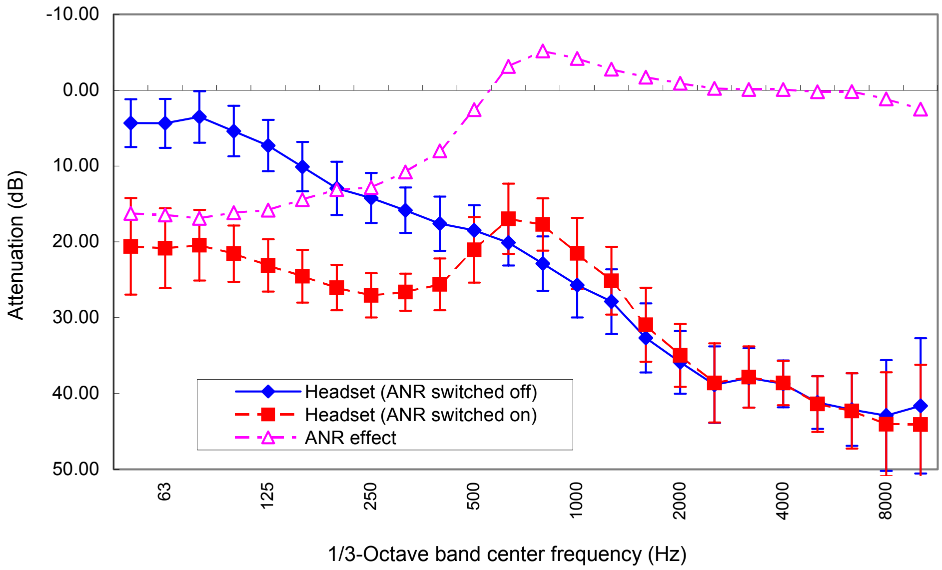

Figure 7. Sound attenuation of a headset with an integrated ANR system (TNO 1997 prototype), measured using a microphone placed near the ear canal entrance with 1/3-octave resolution. Separate curves are shown for a condition with the ANR system switched on, on with the ANR system switched off. The error bars indicate the standard deviation.

Finally, it is important to note that ANR systems are, by the nature of their feedback-based operation, inherently unstable. Heavily fluctuating noises (e.g. low-frequency fluctuations in helicopters related to the rotation frequencies of their rotors), or impulsive sounds, may destabilise an ANR system. This results in the introduction of unwanted sounds, usually at frequencies around the edges of the area in which ANR is active. These noises range from easily recognisable feedback sounds to low-frequency noise (5-50 Hz),

sometimes described as "wharbling." Before introducing ANR for any application, extensive field testing is needed to ensure that stable operation is guaranteed.

4.2.3. Double hearing protection

Introducing double hearing protection, by using earplugs in addition to a headset, is to a certain extent an imposition on the user. While using a headset with ANR is, at least in terms of comfort and ease of use, equal to using single hearing protection, earplugs require care by the user. They must be carefully inserted, using the correct procedures, to prevent loss of attenuation and discomfort. In general, users are more likely to complain about discomfort when using earplugs, especially when these are used for continued amounts of time.

There are many different earplug types on the market, differing in attenuation, price, comfort, durability, ease to clean and maintain, etc. In addition to the many (more or less) disposable earplugs, custom-moulded earplugs are available, which are formed to create a perfect seal once inside the user's ear canal. These offer some advantages over simple earplugs, such as a wide choice in attenuation characteristics, which are determined by the specific acoustic filter built into the plugs.

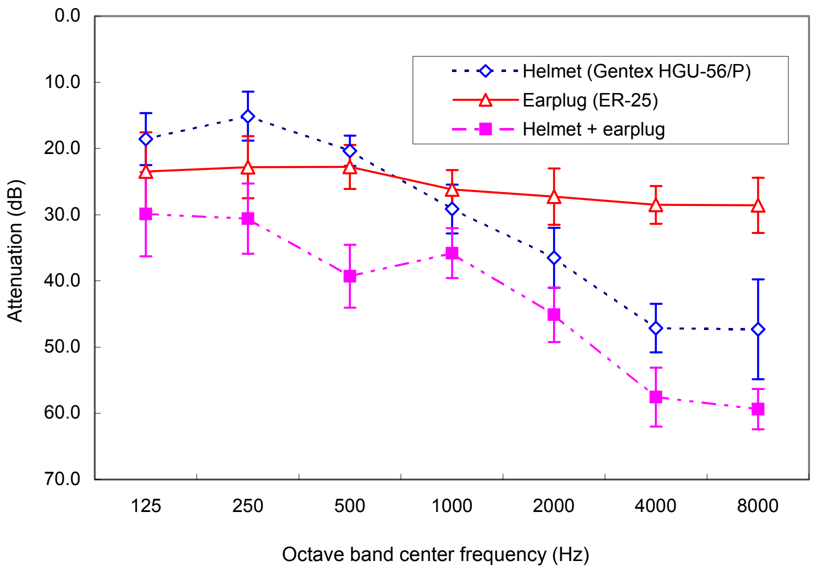

Figure 8. Sound attenuation of a helmet (same as shown in Fig. 6), a custom moulded earplug and the combination of helmet and earplug (double hearing protection). The error bars indicate the standard deviation.

In Fig. 8, an example of attenuation curves for a headset, an earplug, and the same headset and earplug combined are given. The earplug type in this figure was a specific custom moulded earplug, with an acoustic filter designed to provide an attenuation of approximately 25 dB at all frequencies. It can be clearly seen how the combined attenuated is somewhat smaller than the sum of the separate attenuations, especially around 1 kHz. This is due to bone conduction, and also to the acoustic interactions between earcups and earplugs. Hence, the sound attenuation offered by double hearing protection is *not* simply the sum of the attenuation values for the earcups and earplugs separately. Especially at higher sound levels, the overall attenuation is smaller than the sum of individual attenuations. If the combined attenuation for a specific combination has not been measured, it can be estimated from the earplug and earmuff attenuations by means of an empirical formula [1].

4.2.4. Communications EarPlugs (CEP)

The Communications EarPlug (CEP), a concept introduced in the 1990s [11], is essentially an earplug that is used in combinations with a helmet or headset, but with an earphone integrated into the earplug. The obvious advantage, compared with regular double protection, is that the intercom speech is not affected by the earplug. Hence the CEP offers all advantages of double hearing protection, eliminating the major drawback. CEPs are currently used operationally in various nations. Sound attenuation curves similar to Fig. 8 can be obtained.

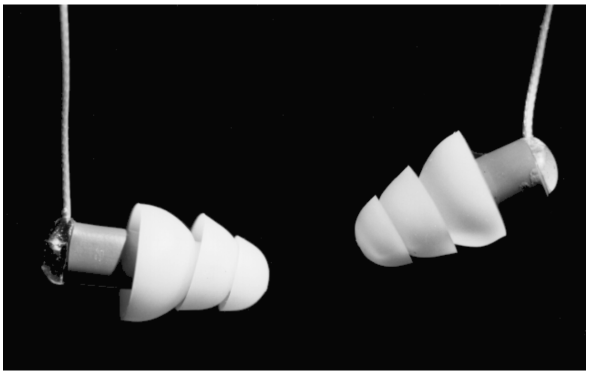

Figure 9. CEP prototypes evaluated for the Royal Netherlands Air Force

Unfortunately, for some applications CEPs have another important drawback: signal leads (thin wires) are required to bring the intercom signal to the earplugs. In practice, this means that after inserting the earplugs and donning the helmet, the user has to connect the signal wires to a socket mounted on the outside of the helmet. These wires can be vulnerable when working in confined spaces; the user is at risk of having the earplugs inadvertently (and painfully) pulled out of the ear upon a wire getting caught behind a protrusion. Also, the wire will introduce an acoustic leak where it passes between the user's skin and the earseal of the earcup, reducing overall sound attenuation somewhat. To eliminate these disadvantages, a wireless version of the CEP was developed by TNO, referred to as w-CEP (fig. 10, [21]).

Figure 10. Earcoils and wireless earplugs (left) and helmet with w-CEP electronics (right) used in wireless CEP field evaluations. The earcoils, with integrated conventional earphones for backup purposes, are built into the earcups of an existing helmet or headset. The helmet with w-CEP electronics is connected to an intercom system in the usual way.

For the w-CEP, a straightforward electromagnetic transmission technique was chosen, based on magnetically coupled coils. Magnetic fields have the desirable characteristic to be highly localised, reducing levels of electromagnetic emission. It has been shown that it is feasible to operate wireless CEPs in compliance with military electromagnetic compatibility standards. Another important characteristic of this approach is that the earplugs (with integrated receiver to pick up the signal, and miniature loudspeaker to reproduce the sound) operate with batteries or any power supply other than the magnetic field itself. Wireless CEPs were shown to have equal performance to conventional CEPs at increased user comfort, and are currently subjected to field trials in several NATO nations.

4.3. Importance of user comfort

We have mentioned user comfort as one of the relevant characteristics of hearing protectors. Intuitively, it is easy to understand why a lack of comfort would cause problems. Uncomfortable earplugs or helmets may distract crew members from their primary activities in situations where concentration is of the utmost importance. Overall, lack of comfort is likely to induce a negative attitude towards the job. However, there is also another important reason to explicitly consider comfort.

When experiencing physical discomfort, people will try to eliminate the cause of this discomfort. This means that uncomfortable hearing protectors are more likely to remain unused. Improper use of these hearing protectors also becomes more likely; for instance, chin straps of helmets are sometimes left loose, or earplugs are only half inserted into the ear canal. This will compromise the performance of the hearing protector.

When forced to work with uncomfortable protection, it is not uncommon for personnel to temporarily remove their protection, to take a break from the discomfort. Unless this happens when the noise is also temporarily stopped (e.g., the vehicle pulled over), the effect of these short intervals without hearing protection is easily is underestimated. This is illustrated by Fig. 11.

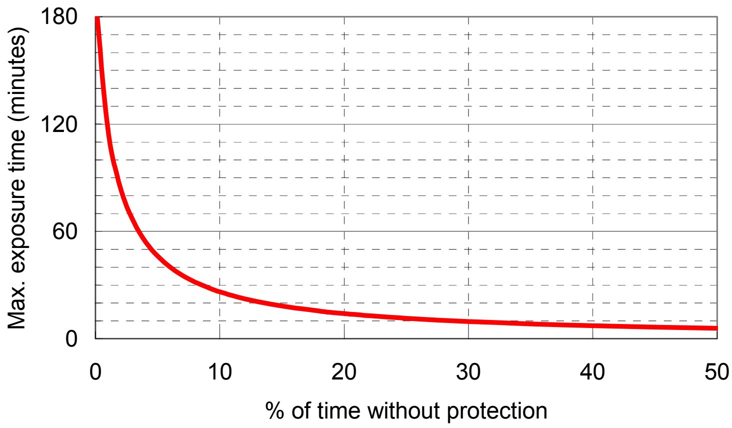

Figure 11. Example of maximum daily exposure times when temporarily removing hearing protectors in noise, calculated according to ISO 1999 (1990) for an L_{Aeq} limit of 80 dBA for an 8-hour working. This example is based on a CH47D Chinook pilot (Fig. 2), wearing single hearing protection in an ambient noise level of 102 dBA. The resulting L_{Aeq} when continuously wearing hearing protection is 84 dBA (max. exposure time approx. 3 hours).

Figure 11 shows how rapidly the maximum exposure time decreases when intervals without protection are introduced. If the hearing protectors are removed about 5% of the time, the maximum delay exposure time is reduced by a factor of 5 (approx. 40 minutes instead of 3 hours). Even if the hearing protection is removed for only 2 minutes during a three-hour flight, the maximum exposure time is reduced by an hour. The impact that these time intervals without protection have underline the importance of user comfort.

5.0 CONCLUSIONS

Noise exposure in military vehicles is an issue that requires explicit and continuing attention. If not dealt with properly, ambient vehicle noise is likely to acutely decrease crew performance in various ways, and in the long term cause hearing problems. Since there has been sufficient information available to the various national Armed Forces to be aware of this, it is not unlikely that military personnel who are currently developing hearing loss on the job will in the future claim for compensation from their governments. For this reason alone the noise problem should be taken seriously.

Developments in the field of personal hearing protection technology are continually improving our abilities to reduce the overall noise exposure of crews. In part, this is simply because hearing protectors are offering ever better sound attenuation. More importantly, advanced hearing protectors are also designed for better speech intelligibility and comfort. Indirectly, this has a clear and important impact on the overall sound levels that crew members allow themselves to be exposed to: better speech intelligibility leads to lower acceptable speech levels, better user comfort leads to better and more consistent use of the available hearing protectors.

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Detailed Analysis or Short Description of the AVT-110 contributions and Question/Reply

The Questions/Answers listed in the next paragraphs (table) are limited to the written discussion forms received by the Technical Evaluator. The answers were normally given by the first mentioned author-speaker.

KN1 S.J. Van Wijngaarden, S. James 'Protecting Crew Members Against Military Vehicle Noise' (TNO-NL, QinetiQ-UK)

This first KN gave, from unpublished and published noise survey data for land- and air vehicles in several Nato Countries, the A-weighted noise level at the positions of exposed crew members (SPL dbA): varying from 80 dBA to more than 110 dBA: values drawing our attention on the importance of the problem and the direct (Short-/Long-term) impacts: a decrease of he hearing acuity, a lower speech intelligibility and a lower perception of the warning signals, with their consequences on the performances of the Crew members. The author concludes on the necessary improving of the hearing protection systems.

1. Discussor's name: R. Bayer
Q. If the military vehicle is hit by a military threat (gun fire) this is a serious danger for the ears of the crew. Is this considered in the investigated systems?
R. Hearing protections need to be designed to attenuate all types of noise, as sofar these can be reasonably expected to occur, down to safe levels. High-level impulsive noises from impacts or commonly from own firing actions are routinely considered during any hearing protector design process. This aspect has not been addressed in-depht in this paper but its relevance is clear.

2. Discussor's name: N. Alem
Q. I did not hear in your presentation any discussion of anti-oxydants as a form of noise preventive protection. What do You think about those drugs as an additional form of noise protection?
R. We did not cover this topic, although we are aware of research carried out in this field. If this research turns out to produce medication that can be operationally used to prevent hearing loss, this effectively adds another line of defence against noise. However some immediate effects of noise (e.g. on speech intelligibility, distraction, fatigue) are not prevented by these means.

3. Discussor's name: D. Sheridan
Q. Are there initiatives to reduce the mass/weight of the entire noise protection system?
R. On any list of requirements for hearing protector design, 'mass' is usually close to the top (specifically for high-G environments). There is a clear desire to reduce mass, which is at odds with the well-known acoustic law that tells us that mass is needed to obtain sound attenuation. Electronics, as used in ANR (Active Noise Reduction) and communications earplugs, help circumvent this problem. For instance, CEPs are currently considered to replace the heavy earcups from aviators' helmets